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Dust and Gas Exposure in Tunnel Construction Work

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Personal exposures to dust and gases were measured among 189 underground construction workers who were divided into seven occupational groups performing similar tasks in similar working conditions: drill and blast crew; shaft-drilling crew; tunnel-boring machine crew; shotcreting operators; support workers; concrete workers; and electricians. Outdoor tunnel workers were included as a low-exposed reference group. The highest geometric mean (GM) exposures to total dust (6–7 mg/m^3) and respirable dust (2–3 mg/m^3) were found for the shotcreters, shaft drillers, and tunnel-boring machine workers. Shaft drillers and tunnel-boring machine workers also had the highest GM exposures to respirable α-quartz (0.3–0.4 mg/m^3), which exceeded the Norwegian occupational exposure limit (OEL) of 0.1 mg/m^3. Shaft drillers had the highest exposure to oil mists (GM=1.4 mg/m^3), which was generated mainly from pneumatic drilling. For other groups, exposure to oil mist from diesel exhaust and spraying of oil onto concrete forms resulted in exposures of 0.1–0.5 mg/m^3. Exposure to nitrogen dioxide was similar across all groups (GM=0.4–0.9 ppm), except for shaft drillers and tunnel-boring machine workers, who had lower exposures. High short-term exposures (>10 ppm), however, occurred when workers were passing through the blasting cloud.

Keywords: α-quartz, epidemiology, exposure assessment, nitrogen dioxide, oil mist, tunnel

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Underground construction has been associated with a variety of exposures, including diesel exhaust, silica dust, oil mist, and nitrogen dioxide.(1–6) Large amounts of dust and gases are liberated when rock is blasted. The composition and amount of dust and gases released after blasting may be influenced by the type of explosive used.(7,8) Dust is also generated by rock drilling and transport operations. Depending on the geology at the work site, high exposures to α-quartz may occur. Diesel-powered machinery, which is used in most underground construction processes, produces carbon monoxide, oxides of nitrogen, various hydrocarbons such as formaldehyde, and particulate matter.(9) Oil mist is produced when mineral oil is sprayed onto machinery for surface protection against concrete spills and onto concrete forms to prevent the concrete from sticking. Changes in the technology have made it possible to complete several phases of the construction process simultaneously, which has probably increased exposure substantially.

Several health effects have been reported due to exposures encountered in underground construction. There have been reports of acute bronchitis among tunnel workers,(10) and diesel exhaust has been shown to cause asthma(11) and airway obstruction.(12) A recent case report concluded that exposure from handling the explosive ammonium nitrate fuel oil (ANFO) caused respiratory irritation.(13) Silicosis, a progressive and sometimes fatal lung disease, has been long recognized in the rock-drilling work force.(14) In a study of tunnel workers exposed to partly decomposed MDI-based grouting it was found that risk for occupational asthma and respiratory symptoms was enhanced.(15) Reductions in pulmonary function over a work shift have been demonstrated in shotcreting operators.(16) Among tunnel workers in Norway, high prevalence rates of chronic obstructive lung disease have been reported, but the etiology is not clear.(17)

Knowledge of exposure-response relationships of lung disease in tunnel workers is limited. This is partly due to the lack of quantitative information on possible exposures. Personal exposure data have been reported in only a few studies,[16] and several authors have stressed the need for more information on exposure levels and job tasks.[18,19] The objective of this study was to characterize the exposures of underground construction workers in an epidemiological study on the relationship between exposure and obstructive lung disease.[17]

BACKGROUND

An underground construction project has three components described by the cross section of the excavated area and the direction of the slope: tunnels (horizontal), shafts (vertical), and rock caverns (horizontal). Tunnels are used in road systems and hydroelectric power plants. Shafts are used in hydroelectric power plants and as a source of fresh air for tunnels. Rock caverns are widely used for oil storage, waste disposal, and car parks.

Underground construction includes a sequence of steps: excavation, rock support, and various finishing works including installation of electricity and road paving. Two methods of excavation are common: the conventional method of drilling and blasting and the use of a full-face tunnel-boring machine (TBM).

The method of drilling and blasting often requires three to four workers: one drill-rig operator, one drill rig helper, one mechanic, and/or one worker to operate the loader. The duration of a drill and blast cycle varies depending on the cross section, but is typically 2–4 hours for drilling; .5–1 hour for charging, blasting, and smoke clearance; about .5–1 hour for removing loose rocks; followed by 2–4 hours for mucking out (hauling) the rock and transporting it to the outside. Removal of loose rock traditionally has been accomplished using hand tools but is now usually performed with a hydraulic jackhammer. The crew is also responsible for the daily maintenance of the loader and the drill rig.

The second method of excavation, a TBM, often is used in heavily populated areas where the traditional blasting method is considered inappropriate because of the release of blasting fumes and noise to the surroundings. The TBM equipment is electrically powered, and the operator of the TBM sits in a closed cabin. Behind the TBM are conveyor belts or cars connected to a train for transport of broken rock out of the tunnel. Each crew consists typically of one operator, a mechanic who can also operate the machine, an electrician, and a loader.

The most common explosives used in drilling and blasting are dynamite, ANFO, and site-sensitized emulsion (SSE). The latter explosive is a water-in-oil emulsion consisting of a nitrate solution and an oil phase. The latter two explosives were used in the study.

Fumes from a drill and blast operation usually are ventilated through the tunnel cavity using a one-way ventilation system. Fresh air is supplied through flexible ventilation ducts into the tunnel face, but contaminated air is not mechanically removed by exhaust ventilation. In a two-way ventilation system two separate ventilation ducts are installed, one to supply fresh air and the other to remove the contaminated air.

In the construction of shafts, a raise climber is common, although a TBM also can be used. The raise climber is a platform that can be raised as the height of the shaft increases. The platform covers the entire cross section of the work area. A compressor installed in the tunnel provides pneumatic pressure to power the drilling equipment and to provide a source of air (albeit contaminated) in the work area. Depending on the size of the platform, there are three or four workers engaged in the drilling and blasting and one mechanic.

Throughout the process and after the excavation has been completed, rock support is performed. The major types of rock support materials are rock bolts, shotcrete (wet concrete), previously cast concrete, and cement based- or chemical-based grout. Before the contractor hands over the project to the client, interior construction and technical installations are done, including installation of electrical power and road paving. (Road paving was not included in the present study.) Tasks and possible exposures of job groups in underground construction are described in Table I.

MATERIALS AND METHODS

Site Selection and Characteristics

Fifteen Norwegian underground construction projects and one project in Italy with a Norwegian contractor were surveyed to assess the personal exposures of underground construction workers. In addition, concrete workers performing ironwork and carpentry work outside the tunnels were included in the study to serve as a reference group for the epidemiological study.[17]

The sites were selected because they were considered to be representative of projects in Norway. The projects built tunnels, rock caverns, and shafts. The excavated cross sections ranged from 13 to 340 m^2. Tunnels were between 500 m and 2500 m long, rock caverns were about 100 m long, and the one shaft in the study was 200 m long at the time of the study. All of the rock caverns and tunnels had a one-way ventilation system. The distance from the end of the ventilation duct to the tunnel face was 40–60 m and the fan flow rate was typically between 1800 and 2500 m^3/min. The shafts had no mechanical ventilation system. In all projects the machinery was diesel powered and the same types of machines were used.

Sampling Strategy

After walk-through surveys of the sites were conducted and information on jobs and tasks was collected, workers were divided into groups performing similar tasks under similar working conditions. Occupational groups included in this study are described in detail in Table I.

A random sample of workers from each group was asked to participate in the study. Participation was voluntary. Exposures to dust and gases were determined by means of personal sampling, and two or more agents were measured for each person for at least two days. Workers were interviewed after sampling for their perception of the normalcy of the exposure conditions.

Under the labor agreements of the workers the work shift was 10 hours with two breaks of 30 min each. The sampling time was limited to 5–8 hours (unless otherwise noted) because of the limited battery capacity of the sampling equipment. High dust concentrations further increased power consumption. However, the sampling time was considered representative for the whole work shift because the sampling periods within a shift were selected randomly and tasks were often repeated during the day.

Sampling Methods and Analysis

Total dust and particulate polycyclic aromatic hydrocarbons (PAHs) were collected on acrylic copolymer membrane filters (Versapore 800, Gelman Sciences, Ann Arbor, Mich.), with a 0.8 μm pore size, fitted in 25 mm closed-faced aerosol filter cassettes (Gelman Sciences) at a sampling flow rate of 2 L/min. The particle mass was measured with a microbalance (Sartorius AG, MC 210 p, Goettingen, Germany), with a detection limit of 0.06 mg (0.063 mg/m^3 based on 8 hours of sampling).

For collection of PAHs and other volatile organic compounds

TABLE I. Occupational Job Groups in Underground Construction

Job Groups	Description of Work	Main Exposures (Sources)
Excavation		
Drill and blast crew	The excavation method is drilling and blasting. The drill rig is operated by one man who is in charge. There is a helper at the face to assist with drill bit changes and hole direction. A third worker does service work on the loader and prepares the explosives. After charging of explosives, the rock is blasted. The blasted rock is transported out of the tunnel or rock cavern by the crew members.	- Diesel exhaust (drilling, loading, and transport equipment) - Nitrogen dioxide and carbon monoxide (diesel-powered equipment, blasting); short-term exposure peaks were observed when workers passed through the blasting cloud - Oil mist and oil vapor (spraying of mineral oil, diesel-powered equipment) - Total dust and respirable dusting containing α-quartz (shotcreting, drilling, loading, and transport operations) - Ammonia (blasting)
Shaft drilling crew	The excavation method is drilling and blasting using a raise climber. They use pneumatic handheld equipment for rock drilling. The only ventilation in the work area comes from the pressurized air used to power the drills. Because the platform is transported out of the shaft before blasting, the workers are generally not in contact with the blasting fumes. However, particular weather conditions may cause blasting fumes to be trapped inside the shaft.	- Oil mist and oil vapor (pneumatic drilling equipment) - Total dust, respirable dust and α-quartz (drilling) - Nitrogen dioxide and carbon monoxide (from blasting)—occasional exposure
TBM crew	The excavation method is drilling. The TBM crew operates a tunnel-boring machine that drills the entire cross section of the tunnel or shaft. The rock is broken up by the drill head, loaded automatically on a conveyor belt or into muck cars connected to a train, and transported out of the tunnel. The drilling machine is electric powered and explosives are not used. There are various dust control systems available.	- Total dust, respirable dust, and α-quartz (drilling)
Protection and Securing Work		
Shotcreting operators	Shotcrete is applied on the tunnel walls for rock support. The operator sits in a mobile chair and directs a nozzle, which sprays wet concrete onto the excavated surface. Some of the rigs have an enclosed cabin where the operator sits. For other rigs the operator stands on the ground next to the rig. Before the work starts the rig is often sprayed with mineral oil to protect its surface. The concrete is mixed offsite.	- Total dust, respirable dust, and α-quartz (shotcreting) - Nitrogen dioxide and carbon monoxide (diesel-powered equipment) - Diesel exhaust (mobile rig, concrete delivery equipment) - Oil mist and oil vapor (spraying of mineral oil)
Support workers	The support workers are responsible for the installation and maintenance of ventilation ducting, compressed air, cables and pipes, and for the transporting of materials. This crew includes mechanics and electricians who "work behind" the excavation crew.	- Total dust, respirable dust, and α-quartz (drilling, mixing concrete) - Nitrogen dioxide and carbon monoxide (diesel-powered equipment, blasting); short-term exposure peaks may occur when corkers are in contact with the blasting cloud - Diesel exhaust (diesel-powered equipment) - Oil mist and oil vapor (diesel-powered equipment)
Finishing Work		
Concrete workers (ironworkers, carpenters)	The tunnel concrete workers do iron and carpentry work after the tunnel has been excavated. Ironworkers first erect a steel form. Welding and torch cutting of the steel is done intermittently but frequently. Carpenters then construct a form in wood and spray it with mineral oil. Moist concrete is poured into the form and allowed to dry. The wooden form is demolished, and occasionally the concrete form is sandblasted to provide a smooth surface.	- Total dust, respirable dust, and α-quartz (sandblasting, drilling) - Nitrogen dioxide and carbon monoxide (diesel-powered equipment, blasting); short-term exposure peaks may occur when workers are in contact with the blasting cloud - Diesel exhaust (concrete delivery equipment, diesel-powered equipment) - Oil mist and oil vapor (spraying of mineral oil) - Metal fumes (welding and torch cutting) - Wood dust (construction and demolition)
Electricians	The electricians are responsible for the final installation of the permanent electrical power supply at the construction site. The excavation has been completed but various finishing work may still be done while the electricians are in the tunnel or rock cavern.	- Metal fumes (welding) - Diesel exhaust (diesel-powered equipment) - Total dust, respirable dust, and α-quartz (drilling)

APPLIED STUDIES

TABLE II. Description of Construction Projects

Project Type	Construction of	Excavated Cross Section (m²)	Number of Workers Sampled	Number of Samples (All Agents Included)	Sampling Period 1996	1997	1998	1999
Railway installation	tunnel	61	11	289	—			
Railway installation	tunnel	111	13	330	—			
Railway installation	tunnel rock cavern	35 150	43	443		—		
Railway installation	tunnel	113	23	215			—	
Road construction	tunnel	130	8	72		—		
Road construction	tunnel	55	1	3			—	
Road construction	tunnel	55	5	20			—	
Road construction	tunnel	50	4	143			—	
Road construction	tunnel	56	1	15		—		
Road construction	tunnel	56	1	8		—		
Road construction	tunnel	58	1	48				—
Cleaning/purification plant	tunnel rock cavern	27 255	18	181		—	—	
Cleaning/purification plant	rock cavern	342	34	159			—	—
Power plant[A]	tunnel	17	11	157		—	—	
Power plant	shaft	13	8	36			—	
Sports center	rock cavern	319	7	90	—			

[A]Italy.

(VOCs) the empty space behind the filter was completely filled with an adsorbent, XAD-2 (SKC, Blandford Forum, UK). Total PAHs and VOCs were measured by gas chromatography (GC) with a flame ionization detector (FID). The detection limits of PAHs and VOCs were 0.2 μg/m³ and 0.01 mg/m³, respectively, based on 8-hour sampling at a flow rate of 2 L/min. The method for sampling and determination of PAHs is described in detail elsewhere.[20]

Respirable dust was collected on 37-mm cellulose acetate filters with a pore size of 0.8 μm using a cyclone separator (Casella T13026/2, London, UK) at a sampling flow rate of 2.2 L/min. The particle mass was measured gravimetrically (with a detection limit of 0.06 mg) and the α-quartz content in the respirable dust sample was measured by X-ray diffraction using National Institute for Occupational Safety and Health (NIOSH) Method 7500.[21,22]

Formaldehyde was collected on a filter impregnated with 2,4-dinitrophenylhydrazine (GMD 570 Formaldehyde passive dosimeter badge, GMD Systems) in a polypropylene housing. Formaldehyde was analyzed by high performance liquid chromatography with an ultraviolet detector, according to information provided by the producer of the dosimeters. The detection limit was 0.003 ppm based on an 8-hour sampling period.

Oil mist was collected on glass fiber filters (Whatman GF [A], Maidstone, England) with a backup filter of cellulose acetate with a pore size of 0.8 μm in 37 mm closed-faced aerosol cassettes (Millipore Corp.). Oil vapor was collected on charcoal (SKC,

TABLE III. Personal Exposure Levels in Tunnel Work by Agent

Agent	Units	Number of Measurements	Number of Persons	Arithmetic Mean	Geometric Mean	Geometric Standard Deviation	Range	OEL Norway[28]	OEL TLV[34]
Total dust	mg/m³	379	155	5.5	3.5	2.6	0.2–56	10	10[D]
Respirable dust	mg/m³	386	151	1.7	1.2	2.4	0.03–9.3	5	3
α-Quartz	mg/m³	299	127	0.13	0.035	5.0	0.001–2.0	0.1	0.05
VOC	mg/m³	106	52	4.0	1.8	5.7	0.004–26	[E]	[E]
Oil mist[B]	mg/m³	194	115	0.47	0.33	2.2	0.02–4.4	1	5
Oil vapor[B]	mg/m³	189	115	4.0	2.6	2.6	0.11–49	50	[E]
Formaldehyde	ppm	34	25	0.020	0.018	1.6	0.005–0.04	0.5	0.3[F]
Nitrogen dioxide[C]	ppm	82	51	0.8	0.6	2.6	0.03–2.9	2[G]	3
Carbon monoxide[C]	ppm	78	45	8.6	5.7	2.5	0.8–40	25	25
Carbon dioxide	ppm	196	104	1100	1000	1.7	87–3100	5000	5000
Ammonia	ppm	177	96	6.0	—[A]		<2.5–60	25	25
Elemental carbon	μg/m³	10	8	220	160	2.2	63–580	[E]	[E]

Note: 47 PAH samples obtained from 25 persons were all below the limit of detection (LOD) (0.2 μg/m³).
[A]Not possible because of too many measurements below LOD (2.5 ppm), n = 88.
[B]Some measurements appear to be below the LOD but were not, due to longer sampling times.
[C]Although individual measurements exceeded the LOD the average GM/AM is below the LOD due to the large number of LOD measurements.
[D]Inhalable dust.
[E]No threshold limit value.
[F]Short-term exposure limit.
[G]Ceiling value.

TABLE IV. Summary of Total Dust, Respirable Dust, α-Quartz, and Elemental Carbon Exposure Concentrations by Job Group

	Total Dust (mg/m³)			Respirable Dust (mg/m³)			α-Quartz (mg/m³)			Elemental Carbon (μg/m³)		
Job Group	n[A]	GM (95% CI)	GSD	n[A]	GM (95% CI)	GSD	LC[A]	GM (95% CI)	GSD	n[A]	GM (95% CI)	GSD
Drill and blast crew	113	2.3 (2.0–2.7)	2.3	117	0.91 (0.78–1.1)	2.3	113	0.025 (0.020–0.031)	3.1	4	340 (110–1000)	3.0
Shaft drilling crew	7	6.1 (1.7–22)	4.1	7	2.8 (0.79–10)	3.9	7	0.33 (0.076–1.4)	4.8	—	—	—
TBM crew	41	6.2 (5.0–7.7)	2.0	43	2.0 (1.6–2.5)	2.0	43	0.39 (0.30–0.52)	2.6	—	—	—
Shotcreting operators	82	6.8 (5.4–8.7)	2.9	82	2.3 (1.9–2.8)	2.4	45	0.014 (0.010–0.019)	3.1	—	—	—
Support workers	16	1.9 (1.1–3.2)	2.8	16	0.67 (0.42–1.1)	2.4	12	0.010 (0.005–0.02)	2.9	—	—	—
Concrete workers	95	3.4 (3.0–3.7)	1.7	94	0.90 (0.81–1.1)	2.0	56	0.033 (0.022–0.049)	4.5	6	100 (70–160)	1.5
Electricians	25	1.4 (1.1–1.8)	1.8	27	0.72 (0.64–0.82)	1.4	23	0.015 (0.011–0.020)	2.1	—	—	—

[A]Number of measurements.
Note:— No measurements.

Blandford Forum, UK). The sampling flow rate for both components was 1.4 L/min, and the sampling period was 2–4 hours. Oil mist was measured by Fourier transform infrared spectroscopy after desorption with Freon 113. A standard solution of the oil that was the source of exposure was measured together with the sample. Oil vapor was measured by GC-FID after desorption with carbon disulfide[23] and with n-decan (Fluka Chemie AG, CH-9470, Switzerland) as a standard. The detection limit for oil mist was 0.008 mg and for oil vapor it was 0.17 mg (0.05 mg/m³ and 1.0 mg/m³ for oil mist and oil vapor, respectively, based on 2-hour sampling).

Elemental carbon was analyzed as a marker of diesel exhaust. Samples were collected on quartz filters in 37 mm closed-faced standard aerosol cassettes with a sampling flow rate of 2.0 L/min. The filters were analyzed for elemental carbon according to NIOSH Method 5040[24,25] with a detection limit of 1.28 μg (1.33 μg/m³ based on 8-hour sampling).

Concentrations of carbon monoxide and nitrogen dioxide were measured with direct-reading electrochemical sensors with a data-logging facility built into the instrument (Neotox-xl personal single-gas monitor, Neotronics Limited, Takeley, UK). An averaging period of one reading every 2 min was selected. The detection limit of nitrogen dioxide and carbon monoxide measurements was 0.2 ppm and 2 ppm, respectively. Direct-reading diffusion tubes (Dräger Aktiengesellschaft, Lübeck, Germany) were used to measure carbon dioxide and ammonia and had a detection limit of 63 ppm and 2.5 ppm, respectively, based on an 8-hour sampling period.

Quality Control

One field blank was taken to the field per day for every 10 particulate samples, with at least 1 blank per day. All blanks were analyzed and found to be below the limit of detection (0.06 mg). The quality control procedures for the gravimetric measurements also included measuring two weights (19.99 mg, SD=0.03 and 49.95 mg, SD=0.04), at the beginning of each weighing session. The weights were calibrated annually by the Norwegian Metrology and Accreditation Service. The laboratory that analyzed formaldehyde, PAH, α-quartz, and oil mist participated in interlaboratory proficiency testing programs.

The response factors of the electrochemical sensors were calibrated every third month by the supplier with calibration gases obtained from Bedford Scientific Ltd., UK (carbon monoxide) and Norsk Hydro, Rjukan, Norway (nitrogen dioxide).

Data Analysis

Using cumulative probability plots, the exposure data were found to be best described by lognormal distributions and were ln-transformed for the statistical analyses. Standard measures of central tendency and distributions (arithmetic and geometric means and geometric standard deviations) were calculated. A small percentage of measurements of nitrogen dioxide (n=5), volatile organic compounds (VOC) (n=5) and respirable dust (n=3) were below the detection limit. The geometric mean exposure (GM_{est}) and the geometric standard deviation (GSD_{est}) were therefore estimated according to Perkins et al.[26] The estimated GMs were used to calculate estimated values below the detection limit:[27]

$$\ln X_{<DL} = \frac{n_{all} \cdot \ln GM_{est} - n_{X>DL} \cdot \ln GM_{X>DL}}{n_{all} - n_{X>DL}}$$

where $X_{<DL}$ = estimated value below the detection limit; n_{all}= all of the samples; GM_{est}= the estimated GM; $GM_{X>DL}$ = geometric mean of samples above the detection limit; and $n_{X>DL}$ = the number of samples above the detection limit.

The Kruskal-Wallis test was used to evaluate the differences in exposure levels among the job groups because of the heterogeneous variances across job groups. To increase independence of the data only the first valid measurement from each person was used in these tests. The Mann-Whitney test was used to evaluate the differences in exposure levels between underground construction workers and outdoor construction workers. Statistical analyses were carried out with SPSS 8.0 (SPSS Inc. Chicago, Ill.).

RESULTS

Measurements were carried out on the 16 work sites over a period of three years between June 1996 and July 1999. Two of the projects were associated with power plants, four with railway

TABLE V. Summary of Nitrogen Dioxide, Carbon Monoxide, and Carbon Dioxide Exposure Concentrations by Job Group

	Nitrogen Dioxide (ppm)					Carbon Monoxide (ppm)			Carbon Dioxide (ppm)		
				Maximum Peak Value[B]							
Job Group	n[A]	GM (95% CI)	GSD	Median	Range	n[A]	GM (95% CI)	GSD	n[A]	GM (95% CI)	GSD
Drill and blast crew	39	0.5 (0.4–0.7)	2.6	2.1	0.1–20	38	9.0 (6.6–12)	2.6	98	990 (870–1100)	1.9
Shaft drilling crew	—	—	—	—	—	—	—	—	8	1300 (1140–1470)	1.2
TBM crew	1	0.2		0.2	—	—	—	—	—	—	—
Shotcreting operators	15	0.4 (0.2–0.8)	3.0	1.4	0.4–3.0	13	2.9 (2.0–4.2)	1.8	12	1000 (610–1700)	2.2
Support workers	4	0.5 (0.1–5.5)	4.5	1.9	0.5–3.9	2	10 (0.2–470)	1.5	12	690 (530–890)	1.5
Concrete workers	14	0.7 (0.4–1.1)	2.3	1.5	0.6–7.4	16	4.3 (3.0–6.2)	2.0	44	1000 (910–1100)	1.4
Electricians	9	0.9 (0.6–1.2)	1.5	3.1	1.7–5.3	9	3.3 (2.0–5.3)	1.9	22	1200 (1100–1300)	1.2

Note: — No measurements.
[A]Number of measurements.
[B]Maximum observed peak value for a 2-min averaging period within shift measurements.

installations, seven with road construction, one with a sports center, and two with cleaning/purification plants (Table II).

All 189 underground construction workers and 20 outdoor concrete workers invited to participate in the exposure assessment did so. The numbers of measured underground construction workers were 52 drill and blast workers; 8 shaft-drilling workers; 11 TBM workers; 17 shotcrete operators; 12 support workers; 61 concrete workers; and 20 electricians. Most of the workers (77%) were monitored on more than one occasion.

Table III gives a summary of the exposure levels by agent. In addition, 47 samples were analyzed for PAH (25 workers), which were all below the detection limit (<0.2 μg/m^3). A Kruskal-Wallis test between job groups showed statistical difference for all agents ($p<0.01$) except for nitrogen dioxide ($p=0.6$), formaldehyde ($p>0.1$), and elemental carbon ($p>0.1$). The mean exposures showed a moderate variability in exposure levels across job groups (Tables IV–VI). A quarter of the geometric standard deviations from all agent- and job group combinations were greater than 3.0.

The highest geometric mean exposures to total dust (>6 mg/m^3) and respirable dust (≥ 2 mg/m^3) were found in shotcreters, shaft drillers, and TBM workers (Table IV). The geometric mean exposure of α-quartz varied from 0.010 mg/m^3 (support workers) to 0.39 mg/m^3 (TBM workers) (Table IV). Ten elemental carbon samples were collected at a single work site (a rock cavern). The geometric mean exposures of the drill and blast workers and the concrete workers were 340 and 100 μg/m^3, respectively (Table IV). The geometric mean exposures to nitrogen dioxide varied from 0.2 ppm (TBM workers) to 0.9 ppm (electricians) (Table V). However, the drill and blast workers were exposed to high peaks of nitrogen dioxide when passing through the blasting fumes during transportation of the blasted rock out of the tunnel. The maximum observed peak value was 20 ppm among these

TABLE VI. Summary of Total Volatile Organic Compounds, Formaldehyde, Oil Vapor, and Oil Mist Exposure Concentrations by Job Group

	VOC (mg/m³)			Formaldehyde (ppm)			Oil Vapor (mg/m³)			Oil Mist (mg/m³)		
Job Group	n[A]	GM (95% CI)	GSD	n[A]	GM (95% CI)	GSD	n[A]	GM (95% CI)	GSD	n[A]	GM (95% CI)	GSD
Drill and blast crew	76	2.9 (2.1–3.9)	4.0	10	0.021 (0.014–0.032)	1.8	80	3.7 (3.1–4.5)	2.3	79	0.31 (0.28–0.35)	1.6
Shaft drilling crew	—	—	—	—	—	—	—	—	—	7	1.4 (0.32–6.3)	5.0
TBM crew	10	1.0 (0.3–4.2)	7.2	—	—	—	10	0.31 (0.23–0.44)	1.6	10	0.07 (0.05–0.11)	1.8
Shotcreting operators	2	18 (1.8–180)	1.3	—	—	—	23	4.2 (3.2–5.6)	1.9	23	0.37 (0.25–0.56)	2.6
Support workers	5	0.3 (0.2–0.3)	1.3	6	0.011 (0.006–0.019)	1.7	10	1.6 (0.48–5.2)	5.3	10	0.29 (0.15–0.55)	2.5
Concrete workers	13	0.3 (0.1–1.0)	7.1	18	0.019 (0.017–0.032)	1.3	41	2.0 (1.8–2.3)	1.5	40	0.45 (0.39–0.51)	1.5
Electricians	—	—	—	—	—	—	25	2.1 (1.7–2.6)	1.7	25	0.29 (0.26–0.32)	1.3

Note:— No measurements.
[A]Number of measurements.

TABLE VII. Personal Exposure Levels in Outdoor Concrete Work Stratified by Agent

Agent	Units	Number of Measurements	Number of Persons	Arithmetic Mean	Geometric Mean	Geometric Standard Deviation	Range	Mann-Whitney[A] Sign
Total dust	mg/m³	35	17	1.2	1.0	1.8	0.3–4.0	<0.01
Respirable dust	mg/m³	40	19	0.3	0.2	1.7	0.1–1.1	<0.01
α-Quartz	mg/m³	40	19	0.003	0.002	1.8	0.001–0.020	<0.01
VOC	mg/m³	34	17	1.8	0.6	7.6	0.004–10	<0.01
Oil mist	mg/m³	16	11	0.18	0.12	2.2	0.1–1.0	<0.01
Oil vapor	mg/m³	17	11	3.0	1.7	3.0	0.28–14	0.10
Formaldehyde	ppm	7	7	0.006	0.006	1.2	0.005–0.007	<0.01
Nitrogen dioxide	ppm	—	—		B			<0.01
Carbon monoxide	ppm	—	—		B			<0.01

[A]Mann-Whitney test between underground construction workers and outdoor concrete workers.
[B]Not measured, assumed to be ambient air concentrations (<0.2 ppm NO_2, <2 ppm CO).

workers for a 2-min averaging period, which was much higher than in the other groups of tunnel workers, for which a maximum of 7.4 ppm was observed (concrete workers) (Table V). In total, 18% of the measurements performed on the drill and blast workers showed exposure peaks >10 ppm. The geometric mean exposures of carbon monoxide varied from 2.9 ppm (shotcreting operators) to 10 ppm (support workers), and carbon dioxide varied from 690 ppm (support workers) to 1300 ppm (shaft drillers) (Table V). The highest geometric mean exposures to oil mist (1.4 mg/m³) were found in shaft drillers (Table VI). Formaldehyde, oil vapor, and VOC levels were low for all workers (Table IV). The outdoor workers as a group had a statistically lower geometric mean exposure ($p<0.01$) to all measured exposures, except oil vapor ($p=0.1$) (Table VII), compared with underground construction workers (Table III).

Respirators generally were not worn by the workers during the work shift, except for workers performing the shotcrete technique and TBM excavation method, both of whom occasionally wore dust masks. One-fifth of the measurements were reported by the workers to have been taken in conditions that were worse than usual, and 5% of the time it was reported to have been better than usual. When the conditions were reported to be worse than usual, the most frequent explanation was that the ventilation system was not functioning.

DISCUSSION

Exposure of these underground construction workers to total dust and respirable dust was found to be substantial when compared with Norwegian occupational exposure limits for total dust and respirable dust (10 and 5 mg/m³, respectively). The geometric mean exposure for total dust varied from 6.8 mg/m³ (shotcreting operators) to 1.4 mg/m³ (electricians). The geometric mean exposure for respirable dust varied from 2.8 mg/m³ (shaft drilling crew) to 0.67 mg/m³ (support workers). The TBM crew also had substantial exposures to these substances. In a study on shotcrete operators[16] a median total dust exposure of 7 mg/m³ was found, which is close to the current findings. Controlling dust emissions during shotcreting is not easy because an aerosol is produced from spraying concrete under high pressure, which induces air streams with high velocity and turbulence. If enclosed cabins on the equipment are not feasible, personal protective equipment is currently the only alternative. When comparing the different excavation processes (drill and blast, TBM, and shaft drilling) it was expected that the drill and blast crew would be less exposed than the other construction workers, which was true (2.3 mg/m³ total dust and 0.91 mg/m³ respirable dust). The lower exposure is likely due to the use of water for dust suppression throughout the drilling procedure. In addition, the drill and blast crew worked a distance from the drill head (~5 m) and fresh air was supplied through the ventilation system, compared with the situation of the shaft-drilling crew, which operated handheld equipment with no mechanical ventilation.

The average respirable α-quartz geometric means ranged from 0.010–0.39 mg/m³. The primary source of α-quartz exposure was rock drilling. The highest exposures of respirable α-quartz were found for the shaft-drilling and TBM crews, which in some cases exceeded the Norwegian occupational exposure limit (0.1 mg/m³) by 5 to 10 times. In total, 21% of the α-quartz measurements exceeded the OEL. In contrast, the drill and blast crew was exposed to geometric mean levels less than one-quarter of the exposure limit. The larger differences across job groups observed for α-quartz most likely indicate differences in geology among the sites as the quartz content in the dust varied among the sites, and sites were spread over the whole of Norway as well as one site in Italy.

The TBM and shaft-drilling methods do not use diesel-powered equipment in the excavation on a regular basis. These workers were mainly exposed to nitrogen dioxide and carbon monoxide from diesel exhaust when driving in and out of the tunnel with a locomotive. Otherwise, such exposure is only occasional. The lower exposure level reflects this difference. The exposures to nitrogen dioxide and to carbon monoxide were similar across all other groups. This is probably because the main source of these gases is diesel exhaust and the workers are exposed to these contaminants as bystanders. A second source of nitrogen dioxide is blasting, and high short-term exposures may occur to workers (most often drill and blast crew, but also support workers and concrete workers) in contact with the fumes in the tunnel after blasting.[7] Short-term measurements of nitrogen dioxide and carbon monoxide on persons passing through areas with fumes were as high as 20 ppm (10 times the Norwegian occupational exposure ceiling limit of 2 ppm) and 120 ppm, respectively, in the current study. The 8-hour TWA of carbon monoxide is 25 ppm, but a short-term exposure limit of 100 ppm is recommended by the Norwegian Labor Inspection Authority.[28]

The source of the oil mist and oil vapor exposure was different across the groups. The source of oil mist and vapor for the shaft drilling crew was from using pneumatic drilling equipment. This group was the highest oil mist-exposed group (GM=1.4 mg/m³), and their average exposure exceeded the Norwegian occupational exposure limit (1.0 mg/m³). The sources of oil mist and oil vapor in the other exposed groups were from diesel exhaust and spraying of oil onto concrete forms. The average oil mist exposure levels of these other groups were 0.29–0.45 mg/m³ except for the TBM crew (<0.1 mg/m³). All groups were exposed to low levels of oil vapor.

Elemental carbon was measured as a marker of diesel exhaust at one site. The geometric group mean exposures of elemental carbon ranged from 100 to 340 μg/m³. The exposure levels were described by the workers as being lower than normal because the activity on the site was less than usual. Samples were not collected at other sites due to study constraints. As diesel-powered equipment was used at all sites, tunnel workers were likely to be exposed at similar or higher levels of elemental carbon. Stanevich et al.[29] found in a potash mine arithmetic group mean exposures ranging from 53–345 μg/m³, which were somewhat lower than in the current study.

Dusts and gases generated outdoors may rapidly disperse in the outside air, and therefore, the exposure levels of diesel exhaust and gases of outdoor workers are likely to be low. However, these workers may be exposed to dust that it is emitted close to the workers by drilling or by cleaning of concrete forms with pneumatic air. Anecdotal information from the employers under study indicated that occasionally outdoor concrete workers held jobs in the tunnel for periods of months or years due to a limited number of concrete workers. During these periods their exposures would be the same as for underground concrete workers.

Respiratory effects of exposure to several of the measured agents have been reported. Rudell et al.[30] showed that exposure to diesel exhaust for 1 hour may induce bronchoalveolar inflammation in healthy human volunteers. In another study, Blomberg et al.[31] found that in healthy subjects, exposure to 2 ppm nitrogen dioxide for 4 hours caused neutrophilic inflammation in the airways. In the current study tunnel workers in contact with blasting fumes were exposed to levels much higher than this (20 ppm), although exposure to these levels generally did not last more than a few minutes depending on the efficiency of the ventilation system. However, the GM exposures to nitrogen dioxide of job groups was substantial (0.2–0.9 ppm). A study of machine shop workers concluded that occupational asthma due to oil mists was common,[32] and α-quartz exposure has been shown to be an independent predictor for spirometric airflow limitation.[33] This suggests that exposure to diesel exhaust, nitrogen dioxide, and oil mist, as well as α-quartz, may all contribute to the observed reduction in lung function among tunnel workers.[17] Evaluating exposure-response associations may elucidate which of these are the causal agents. Such information is crucial for setting priorities for exposure prevention measures. Technological solutions are needed for exposure prevention, because many workers feel uncomfortable wearing a respirator throughout a work shift and therefore seldom use respirators. Moreover, the Norwegian Labor Inspection Authority does not accept respirator use on a permanent basis as a preventive measure. Possible technological solutions are to exchange diesel-powered equipment for electrically powered equipment, improve ventilation system, or use enclosed and ventilated cabins.

CONCLUSION

Underground construction workers are simultaneously exposed to a variety of chemical agents including dust, diesel exhaust, α-quartz, oil mist, nitrogen dioxide, and carbon monoxide, in some cases at levels substantially above the exposure limits. The results of the exposure measurements and observation of poor respiratory health suggest that a better control of exposures is needed.

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REFERENCES

1. **Bavley, H.:** Some environmental aspects in the construction of the city tunnel. *Ind. Hyg. Quartely 11*:125–129 (1950).
2. **Burns, C., F. Ottoboni, and H.W. Mitchell:** Health hazard and heavy construction. *Ind. Hyg. J. 23*:273–281 (1962).
3. **Sullivan, P.A., K.M. Bang, F.J. Hearl, and G.R. Wagner:** Respiratory disease risks in the construction industry. *Occup. Med. 10*:313–334 (1995).
4. **Ringen, K., J. Seegal, and A. Englund:** Safety and health in the construction industry. *Annu. Rev. Pub. Health 16*:165–188 (1995).
5. **Wong, P.H., W.H. Phoon, and K.T. Tan:** Industrial hygiene aspects of tunneling work for the mass rapid transit system in Singapore. *Appl. Ind. Hyg. 3*:240–243 (1988).
6. **Petersen, J.S., and C. Zwerling:** Comparison of health outcomes among older construction and blue-collar employees in the United States. *Am. J. Ind. Med. 34*:280–287 (1998).
7. **Søstrand, P., K. Lian, and T. Myran:** The contribution of inorganic gases from diesel exhaust and from the blasting cloud during excavation of a tunnel. *Occup. Hyg. 4*:1–13 (1997).
8. **Chaiken, R.F., E.B. Cook, and T.C. Ruhe:** *Toxic Fumes from Explosives: Ammonium Nitrate-Fuel Oil Mixtures* (Report of Investigations No. 7867). Philadelphia: International Bureau of Mines, 1974.
9. **Scheepers, P.T.J., and R.P. Bos:** Combustion of diesel fuel from a toxicological perspective. *Int. Arch. Occup. Environ. Health 64*:149–161 (1992).
10. **Henry, M.G.:** Acute tunnel gas bronchitis—with case report. *Ind. Med. 8*:477–480 (1939).
11. **Wade III, J.F., and L.S. Newman:** Diesel asthma: Reactive airways disease following overexposure to locomotive exhaust. *J. Occup. Med. 35*:149–153 (1993).
12. **Ulfvarson, U., R. Alexandersson, M. Dahlquist, U. Ekholm, and B. Bergström:** Pulmonary function in workers exposed to diesel exhaust: The effect of control measures. *Am. J. Ind. Med. 19*:283–289 (1991).
13. **Donoghue, A.:** Inhalation of ammonium nitrate fuel oil explosive (ANFO). *Occup. Environ. Med. 55*:144(1998).
14. **National Institute for Occupational Safety and Health (NIOSH):** *NIOSH Alert: Request for Assistance in Preventing Silicosis and Deaths In Rock Drillers* (DHHS publication no. 92–107). Cincinnati, OH: NIOSH, 1992.
15. **Ulvestad, B., E. Melbostad, and P. Fuglerud:** Asthma in tunnel workers exposed to synthetic resins. *Scand. J. Work. Environ. Health 25*:335–341 (1999).
16. **Kessel, R., M. Redl, R. Mauermayer, and G.J. Praml:** Changes in lung function after working with the shotcrete lining method under compressed air conditions. *Br. J. Ind. Med. 46*:128–132 (1989).
17. **Ulvestad, B., B. Bakke, E. Melbostad, P. Fuglerud, J. Kongerud, and M.B. Lund:** Tunnel workers are at increased risk of obstructive pulmonary disease. *Thorax 55*:277–282 (2000).
18. **Burkhart, G., P.A. Schulte, C. Robinson, W.K. Sieber, P. Vossenas, and K. Ringen:** Job tasks, potential exposures, and health risks of laborers employed in the construction industry. *Am. J. Ind. Med. 24*:413–425 (1993).

19. **Susi, P., and S. Schneider:** Database needs for a task-based exposure assessment model for construction. *Appl. Occup. Environ. Hyg. 10*: 394–399 (1995).

20. **Bentsen, R.K., H. Notø, K. Halgard, and S. Øvrebø:** The effect of dust-protective respirator mask and the relevance of work category on urinary 1-hydroxypyrene concentration in PAH exposed electrode paste plant workers. *Ann. Occup. Hyg. 42*:135–144 (1998).

21. **National Institute for Occupational Safety and Health (NIOSH):** Silica, crystalline, by XRD Method 7500. In *NIOSH Manual of Analytical Methods,* 4th ed. (DHHS publication no. 98–119). Cincinnati, OH: NIOSH, 1998.

22. **Bye, E., G. Edholm, B. Gylseth, and D.G. Nicholson:** On the determination of crystalline silica in the presence of amorphous silica. *Ann. Occup. Hyg. 23*:329 *Silica, crystalline, by XRD Method 7500,*334 (1980).

23. **Woldbæk, T., and M. Brendeford:** Validation of FTIR as an analytical method for determination of oil mist and oil vapor in workplace atmosphere. *42. Nordiske Arbeidsmiljømøtet (42. Nordic Meeting on Work Environment)* (1993). [In Norwegian].

24. **National Institute for Occupational Safety and Health (NIOSH):** Elemental carbon (diesel particulate) Method 5040. In *NIOSH manual of analytical methods,* 4th ed. (2nd suppl.). Cincinnati, OH: NIOSH, 1998.

25. **Birch, M.E., and R.A. Cary:** Elemental carbon-based method for occupational monitoring of particulate diesel exhaust: Methodology and exposure issues. *Analyst 121*:1183–1190 (1996).

26. **Perkins, J.L., G.N. Cutter, and M.S. Cleveland:** Estimating the mean, variance, and confidence limits from censored (< limit of detection), lognormally distributed exposure data. *Am. Ind. Hyg. Assoc. J. 8*:416–419 (1990).

27. **Eduard, W., and B. Bakke:** Experiences with task-based exposure assessment in studies of farmers and tunnel workers. *Nor. J. Epidemiol. 9*:65–70 (1999).

28. **Norwegian Labor Inspection Authority:** *Norwegian list of occupational exposure limits* (Publication no.361). Oslo, Norway: Tiden Norsk Forlag AS, 1996.

29. **Stanevich, R.S., P. Hintz, D. Yereb, M. Dosemeci, and D.T. Silverman:** Elemental carbon levels at a potash mine. *Appl. Occup. Environ. Hyg. 12*:1009–1012 (1997).

30. **Rudell, B., A. Blomberg, R. Helleday, et al.:** Bronchoalveolar inflammation after exposure to diesel exhaust: Comparison between unfiltered and particle trap filtered exhaust. *Occup. Environ. Med. 56*: 527–534 (1999).

31. **Blomberg, A., M.T. Krishna, V. Bocchino, et al.:** The inflammatory effects of 2 ppm NO_2 on the airways of healthy subjects. *Am. J. Respir. Crit. Care Med. 156*:418–424 (1997).

32. **Robertson, A.S., D.C. Weir, and P. Sherwood Burge:** Occupational asthma due to oil mists. *Thorax 43*:200–205 (1988).

33. **Humerfelt, S., G.E. Eide, and A. Gulsvik:** Association of years of occupational quartz exposure with spirometric airflow limitation in Norwegian men aged 30–46 years. *Thorax 53*:649–655 (1998).

34. **American Conference of Governmental Industrial Hygienists (ACGIH):** *TLVs and BEIs.* Cincinnati, Ohio: ACGIH, 2000.